A Rapidly Relocatable, Coupled, Mesoscale Modeling System for Naval Special Warfare

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Award Number: N0001407WX20188
https://jaws.nrlmry.navy.mil

LONG-TERM GOALS

This project was one coordinated component of a larger combined 6.2/6.4 Rapid Transition Project (RTP) to address support for specific Naval Special Warfare (NSW) operational decisions that are affected by fine scale meteorology and oceanography (METOC) processes. Our overall goal was to develop technology for a unique, rapidly-relocatable, coupled air-sea, high-resolution data assimilation system capable of utilizing the diverse, highly perishable, on-scene environmental data collected by NSW forces. The coupled air-sea forecast system we developed improves the forecasts and characterizations of the impact of rapidly changing, operationally significant environmental situations over the products that are routinely available today. We envision future transitions to incorporate nowcasting and forecasting technology within NSW and other naval operations by continuously blending all data and projecting the fused information forward into the near future, applying the information to a wide array of mission specific decisions.

This project supported the Oceanographer of the Navy's (N84) Littoral Battlespace Sensing, Fusion and Integration (LBSF&I) initiative and directly addressed the Commander, Naval METOC Command (CNMOC) Battlespace on Demand (BonD) environmental battlespace characterization strategy, including meeting CNMOC modeling roadmap reach-back requirements.

OBJECTIVES

The transition from open-ocean to littoral operations has increased the importance of understanding the detailed, complex environmental effects on weapon and sensor systems, particularly in shallow water operations. However, the environmental data collection network is relatively sparse and thus cannot adequately sample and characterize the battlespace environment. The NRL METOC coupled data assimilation telescoping strategy seeks to ameliorate this situation since given a few observations, model products are the only source of information that provide a realistic 4-D representation of the oceanic and atmospheric state consistent with known dynamical and physical relationships. The resulting system must be optimized to both provide the required data and products to both the end users and mission planning systems while efficiently utilizing available communications capability. Currently, the METOC specialist must interpret environmental products for the warfighter who then makes decisions and manual adjustments to weapon and sensor systems by trial and error. Efficient

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
30 SEP 2007	**Annual**	**00-00-2007 to 00-00-2007**

4. TITLE AND SUBTITLE **A Rapidly Relocatable, Coupled, Mesoscale Modeling System For Naval Special Warfare**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Research Laboratory,Marine Meteorology Division,7 Grace Hopper Avenue,Monterey,CA,93943-5502**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
code 1 only

14. ABSTRACT
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15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**Same as Report (SAR)**	**9**	

data collection, communications, processing, quality control, and automation are the keys to recovering this valuable time lost in a warfare situation.

The specific objectives of this project within the larger effort were: 1) to design and develop the prototype coupled air-sea modeling and data assimilation capability within the existing NRL Coupled Ocean/Atmosphere Mesoscale Prediction System – On Scene (COAMPS-OS®) system, including a comprehensive Graphical User Interface (GUI) for easy set-up of the coupled system; 2) to create the data acquisition and processing software necessary to utilize the variety of NSW collected data, including oceanographic, atmospheric, and bathymetric observations; and 3) to obtain end-user buy-in through a series of verification and validation experiments that encompassed NSW-relevant scenarios and operations. Through these interactions with NSW operators, we identified additional capabilities that could be provided if follow-on support is received. These additional capabilities are listed in the Results Section and detailed in a supporting letter from the NSW community to the Commander, Naval METOC Command (CNMOC).

APPROACH

Utilizing the NSW Mission Support Center (MSC) as a beta test facility, we developed and tested a unique capability for coupling atmospheric and oceanographic models, and for assimilation of some METOC data from NSW sensors in near real time, within the globally-relocatable framework provided by COAMPS-OS. By using the operational systems for development, our strategy allows for demonstrating operational support while at the same time providing a technology that can be scaled to larger systems and transitioned to Production Centers, i.e. Fleet Numerical Meteorology and Oceanography Center (FNMOC) or the Naval Oceanographic Office (NAVO).

To meet the challenge of utilizing METOC data available at asynoptic times collected by forward-deployed NSW units, COAMPS-OS has been enhanced to support an integrated ocean 3-dimensional analysis system (Navy Coupled Ocean Data Assimilation; NCODA), an ocean circulation model (Navy Coastal Ocean Model; NCOM), and an integrated shallow-water wave modeling capability (Simulating Waves Near-shore; SWAN). Initially, NCODA and NCOM have been integrated into the COAMPS-OS software suite and the existing COAMPS GUI enhanced to control the oceanographic domain and other ocean model and data assimilation parameters. Software to access and process lateral boundary conditions from the Global NCOM at NAVO was developed to support the limited area NCOM forecast model. Additionally, in collaboration with the NSW warfighters at the MSC, we developed automated output products from the system that are tailored to their mission requirements. These forecast products have been evaluated with data from the information-rich Southern California and Hawaii areas, leveraging Intensive Observing Periods (IOP) for other experiments and NSW training and certification operations.

Another key element of our approach was the close coordination with other projects at NRL. NRL is already established as a leader in the development of high-resolution atmospheric and ocean models, and air-sea coupling. The atmospheric component of COAMPS is a state-of-the-art mesoscale model, providing high-resolution (as fine as 1 km grid spacing) guidance for many regions over the earth. The NRL NCOM ocean model was developed in an ONR-sponsored program at the NRL Stennis Space Center (NRL-SSC). NRL Monterey (NRL-MRY) and NRL-SSC are independently running NCOM coupled with COAMPS and testing the relocatability and robustness of the coupled system at various

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geographic locations and with different coupling strategies. Our approach was to merge these two components into one unified coherent system to help standardize and facilitate (through ease of use) the exploration of air-sea interactions important for NSW operations.

In the technical assessment of the environment as proposed, it is important not to lose sight of the end-user needs and requirements from both the METOC community and the warfighters. Without a feedback mechanism between the science and development process and the end-user, it is possible to be scientifically and technically correct, but produce results that are not used or useful. To this end, we coordinated with an NRL 6.2 Base project for Coupled Data Assimilation, with another NRL project for coupling using the Earth System Modeling Framework (ESMF), and we had a well-defined periodic involvement of selected end-users from the NSW community that helped solidify interoperability and user-specific product and process issues.

WORK COMPLETED

Early in the project a workshop on oceanographic studies in the SOCAL area was held at Scripps Institute of Oceanography to identify ongoing and planned oceanographic studies that can be used for testing the coupled modeling system. A number of coordination meetings were held at NRL-MRY to discuss the coupled modeling tools and approaches. The coupling strategy was defined and software to provide COAMPS data for NCOM and SWAN was developed. NCODA (Message Passing Interface version) was installed and tested in COAMPS-OS for providing ocean analyses initial conditions for both COAMPS and NCOM. Modifications to the COAMPS-OS GUI were developed to accommodate controlling NCOM and SWAN. A small (20 computational processors) LINUX cluster was procured and set up at NRL-MRY for model integration, software development, and verification testing and evaluation.

We have merged the latest operational COAMPS version 4.3, including the Multivariate Optimum Interpolation (MVOI) and components of the NRL Atmospheric Variational Data Assimilation System (NAVDAS version 2.10), with the NCODA version 2.2, NCOM version 2.6, and SWAN version 40.51 model components into a single coupled system using the COAMPS-OS version 1.2 framework running on the LINUX testbed cluster. COAMPS, NCOM, and SWAN are loosely-coupled and cycling on the system for many geographic areas. Since the development of NCOM is proceeding in parallel with the coupled modeling system, we have developed an incremental release strategy for integrating COAMPS and NCOM into COAMPS-OS culminating in a planned October 2007 delivery. The coupled system has been designated as COAMPS-OS version 2.0. At the completion of this project at the end of FY07, the software is not quite ready for designation as a tagged release yet, which would get it to the alpha development stage (where we can actually package up the software and test the release plan). Our estimate is that COAMPS-OS V2.0 will be ready to transition to beta at FNMOC near the end of the 2007 calendar year, about one quarter behind our target date planned three years ago. However, with the large increase in complexity and computational load associated with the multiple models in COAMPS-OS V2.0, we expect that FNMOC will keep the system in beta testing much longer than the typical two weeks for other COAMPS-OS releases - just how long is hard to predict (although FNMOC is very eager to get the coupled system running).

COAMPS-OS was installed at NRL-SSC on a 4-processor LINUX platform. Observational data and NOGAPS boundary conditions were provided by the Global Ocean Data Assimilation Experiment (GODAE) server at FNMOC. After a period of testing, the system was put into routine use in May 2007. The system was upgraded to 8-processors by late September 2007. The NRL-SSC system and the NRL-MRY development cluster were used to run a variety of experimental jobs testing and validating the coupled modeling system. Listed below are several examples:

BP07/LASIE: A nested NCOM (with tides and rivers) was run in a free-running (non assimilative mode) for an extended period from March 15 – July 15, 2007 in support of the Battlespace Preparation 07 (BP07) and Ligurian Sea Air-Sea Interaction Experiment (LASIE) with the NATO Undersea Research Centre (NURC) and other partner nations. A 4 km outer nest forced inner nests of resolutions of 2 and 0.6 km. We discovered that the global WAVE WATCH-III (WW-III) model that provided boundary conditions for SWAN treats the Mediterranean Sea as land, so we investigated running a regional WW-III over the Mediterranean. These results were presented during the REA ’07 Conference held near NURC September 25-27, 2007.

AUVFEST ‘07: A 45/15/5/1.67 km nested COAMPS forecast was run by NRL-MRY in support of AUVFEST ’07 which took place during June 1-14, 2007 at Panama City, Florida. COAMPS was run on the NSW development cluster. COAMPS output was placed on an ftp site and made available to NRL-SSC which ran a 15/5/1.67 km nested NCOM for the same geographical coverage areas as COAMPS. Tides and monthly river discharges were included in the NCOM forecasts. A preliminary evaluation of NCOM currents near Panama City, FL showed reasonable skill. Analysis was also completed to evaluate the performance of NCOM both with and without NCODA data assimilation. During AUVFEST, NCOM output for nests 2 and 3 were provided in netCDF format to developers of a Mission Planning Toolkit. Additionally, these COAMPS fields were successfully utilized by NAVO for their high-resolution SWAN predictions for Panama City, FL. NRL-SSC and NAVO coordinated efforts in providing Delft3D predictions for AUVFEST areas 4 & 10. NRL-SSC is also evaluating the Delft3D results against observational data collected during AUVFEST.

RADAR’07: COAMPS-OS was used to establish a 45/15/5 km COAMPS grid centered off the Southwest Portuguese Coast in support of the RAndom field of Drifting Acoustic Receivers (RADAR'07) sea trial, 9-16 July 2007, near Setúbal, Portugal. A 3 km and nested 600 m NCOM grid was forced with COAMPS surface winds and heat fluxes. The NCOM forecasts included tides and monthly river discharge. Hourly COAMPS ‘flat files” were utilized by NCOM. Lateral boundary conditions were provided by the Global NCOM. A problem with the precision (floats vs. integers) was identified and fixed in the map zoom capability. SWAN was set up to run for two of the nests. Interestingly, SWAN failed after integrating for all times for the coarse mesh (0.2 deg resolution, 25x23 grid points), but completed with no problems when the resolution was increased. The objective of RADAR07 was to acquire acoustic low frequency (< 2 kHz) and high frequency (10-20 kHz) data for testing the network tomography concepts for shallow water rapid environmental assessment using numerical ocean models. Participants included the Portuguese Hydrographic Office, NRL and NURC.

Vocals: This area consisted of two nests (18 and 6 km) off the coast of Peru/Chile with NCOM enabled for both grids at 6 and 2 km resolution. The very first test run failed during NCOM integration, but subsequent runs for both grids completed successfully.

The coupled modeling system was also run at NRL-MRY for an NSW exercise near Kaena Pt., HA, and in support of the ONR AESOP float deployments in the Western Pacific. Figure 1 shows the cascading model results with the COAMPS multi-nest driver forcing the multiple SWAN runs down to 0.0012 deg grid spacing, all accomplished with COAMPS-OS. Figure 1 also shows the SWAN and COAMPS results used to drive the Delft3D hydrodynamic surf zone model at 40 m grid spacing. The

Delft3D products were then used in the NSW Seal Delivery Vehicle (SDV) Certification Exercise (CERTEX).

RESULTS

The scientific and technical challenges of developing a unique, globally-relocatable, coupled air-ocean data assimilation and forecasting system are daunting, particularly while trying to coordinate with multiple groups of scientists and trying to focus the operational support on issues relevant to the NSW warfighter. The NSW operational requirements of 1 km horizontal resolution (requiring approximately 250 m grid spacing) and 5 h nowcasts to 96 h forecasts will not be realized in the near future. Based on what we discovered as we plowed this ground, we have achieved our goals to create a foundation for future progress by prototyping the system and demonstrating an enhanced capability that will transition to operations. The issues identified and our recommended solutions for data collection and connectivity (communications) and security (both OPSEC and information technology) will need to be addressed by the broader Navy METOC operational community.

As examples of some of the needs in the science and technology areas, we include a better understanding the physical oceanographic and atmospheric processes at the air-sea boundary, including the development and testing of sub-grid scale parameterizations required for the forecast models; development of sampling strategies for unmanned vehicles and other deployed sensor arrays; development of <u>coupled</u> data assimilation, data fusion, and analysis techniques; and validation of the analysis and forecasting technologies using a wide variety of observation data including ships, aircraft, satellites and other remote sensors.

The coupled system will need real-time access to all available atmospheric and ocean observations. The system will also need real-time access to the latest available analysis and forecast fields from both NOGAPS and global NCOM (run at NAVO), for lateral boundary conditions, and for initial conditions in the event of a cold start. Furthermore, the system must include all relevant surface data bases (e.g., terrain, bathymetry, land/sea boundary, ground wetness, ice cover) and would benefit from a single, consistent combined global terrain-bathymetry-coastline database. If WW-III fields are not available for lateral boundary conditions, global WW-III can be run within COAMPS-OS to provide boundary conditions for regional SWAN forecast areas.

The completely coupled air-ocean-wave system has been demonstrated to meet the goals of not taking more than 50% more computational time, 50% more memory, and 100% more disk space than the uncoupled atmospheric COAMPS model takes alone. These numbers will vary with individual runs since the actual resource requirements vary considerably based on the areas to be covered and the exact configuration of the model grids compared to the atmospheric model grid (ocean models are typically operated at higher resolution than the atmospheric driver grids).

This software developed in this project has transitioned to 6.4 projects supporting the continued development and operational transition of COAMPS-OS. We are collaborating with the Battlespace Environments Institute in the development and testing of an ESMF compliant version of the coupled COAMPS/NCOM system which we plan to implement in FY08 and then compare the one- vs. two-way coupled results. We also anticipate submitting a journal article on the two-way coupled modeling system in FY08. The spiral development of a one-way and then a two-way coupled system follows the transition strategy submitted and approved by the Atmospheric Modeling Oversight Panel (AMOP). We have also coordinated development with the NURC, Scripps Institution of Oceanography, and other ONR supported experiment programs for in-situ observation data sets that can used to further study the performance of the integrated modeling capability. In collaboration with the Naval Special Warfare operators, we have developed the following list of some operationally useful capabilities that could enhance the current coupled modeling system and better support NSW operations.

- Global NCOM service interface for lateral boundary condition fields.
- Common bathymetry, topography, shoreline database.
- Bathymetry data ingest, merge, and editing capability.
- Development of the capability to deliver the forecast fields to a relevant forecaster tool or mission planning environment, for example using geospatial information system (GIS) formats to interface with the Special Operations Mission Planning Environment (SOMPE-M).
- Better integration of NCOM, SWAN, and WW-III graphics within COAMPS-OS.
- Addition of netCDF format output option for all model output fields.
- Development of an integrated COAMPS-OS GUI to download tailored data sets for Delft3D.
- Integration of ocean and wave fields support into ISIS at FNMOC.
- Fully nested NCOM implementation.
- Full PC-Tides model integration.
- Full rivers integration including dynamic database and interaction with bathymetry editor.
- Incorporation of NCOM and SWAN run time and file system estimates in the COAMPS-OS GUI.
- The addition of NCOM and SWAN training material to the COAMPS-OS web pages.
- Enhancement of the atmospheric Rapid Environmental Assessment (REA) capability in COAMPS-OS to include NCOM, SWAN, and WW-III.

IMPACT/APPLICATIONS

NSW operations are optimally supported by dedicated mesoscale atmospheric and oceanographic modeling responsive to temporal and spatial requirements. NSW forces operate and employ platform/vehicles, weapons, and sensors especially sensitive to the environment – both atmospheric and oceanographic. NSW operations are focused on small geographic areas for short duration. Rapid spin-up of globally relocatable models and production of model data for the warfighters over relatively short time frames is important to maintain advantages over adversaries. Mission analysis and execution benefits from high resolution atmosphere and oceanographic modeling that accurately characterize and forecasts the battlespace and distributes the important information to NSW systems.

Thresholded atmospheric and oceanographic requirements for NSW operations and platforms/vehicles are documented in SOCOM Directive 525-6 and NSW Mission Planning guides. High-resolution modeling coupled with the NSW Director of Oceanographic Operations' initiative to deploy sensors (via Environmental Reconnaissance Teams) with data accessible from the MSC, will improve the accuracy of high resolution forecasts supporting NSW operations. Model experts present in the MSC will allow for the input into the deployment of METOC sensors to best support the models. In addition, specific lessons learned from combat operations in support of Operations Iraqi Freedom and Enduring Freedom and more recent combat operations highlight the shortfall that exists today in the absence of dedicated coupled mesoscale modeling. Tactical Decision Ads (TDAs), such as the Advanced Refractive Effects Prediction System (AREPS) and the Target Acquisition Weapons Software (TAWS), are used to support NSW operations and will also benefit from the increased resolution and accuracy of high resolution model data. Coupling of atmospheric and oceanographic models will also provide more accurate waves and surf in the near-shore area using the Delft3D model. The MSC is a supportive environment for beta-testing systems and can provide an ample opportunity to demonstrate technologies and capabilities in multiple exercises and operations.

Coupled data assimilation technology, including data fusion algorithms, automated data quality control software, and data assimilation software will transition to the FNMOC Centralized Atmospheric Analysis and Prediction System (CAAPS) and to the NSW MSC via reach-back to FNMOC. This research effort bridged the meteorological and oceanographic research communities in the numerical prediction, data fusion, and data assimilation areas. Some key issues in coupled systems development that have been addressed by this effort are also important to further improve environmental prediction and assessment technology currently used by many scientists in the research and development community. These developments can be applied to other weather and ocean forecasting and nowcasting systems used by civilian agencies such as the Department of Homeland Security, NASA and FAA, and within the broader research and development community.

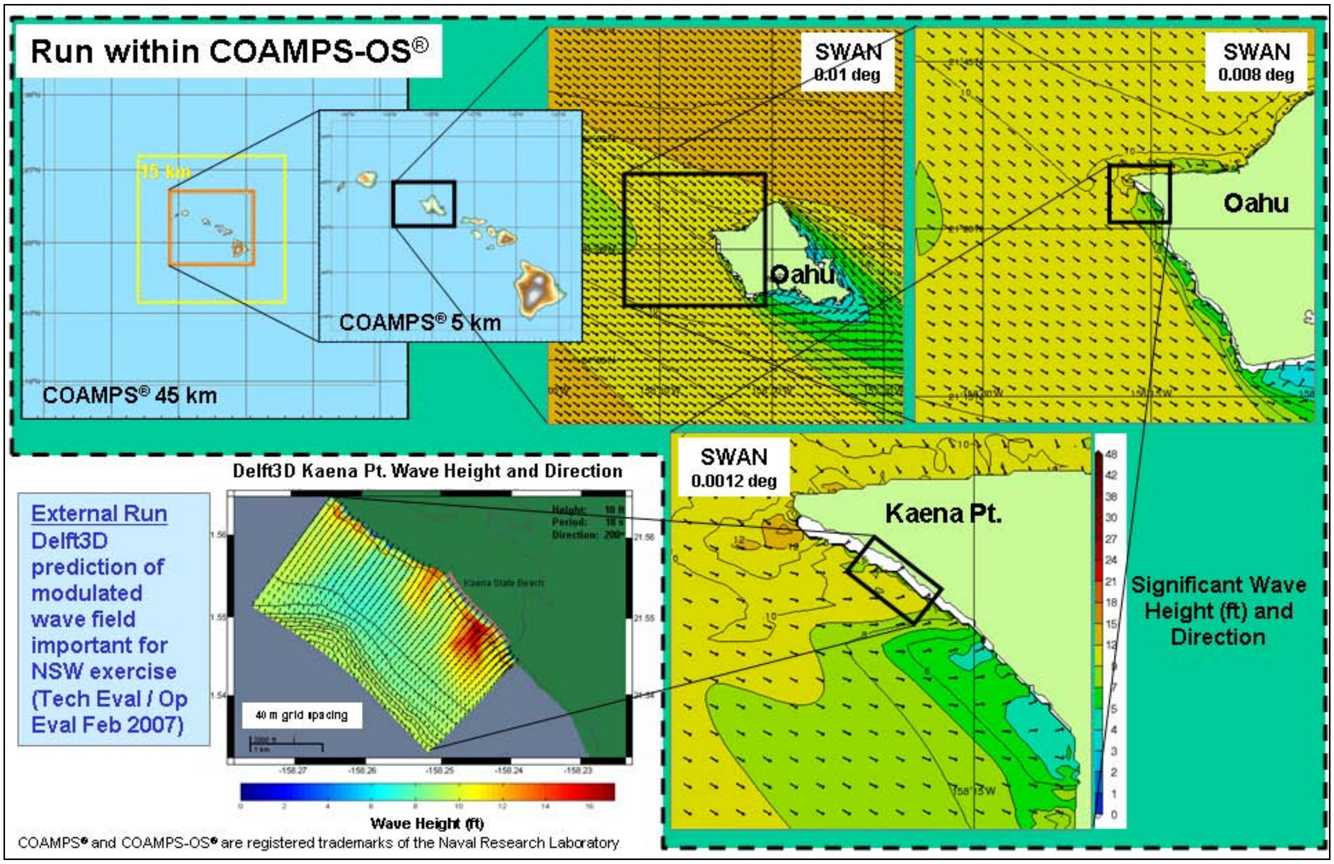

Figure 1. Schematic showing how the coupled modeling system was run at NRL-MRY for an NSW exercise near Kaena Pt., HA. The figure shows the cascading model results with the COAMPS multi-nest driver forcing the multiple SWAN runs down to 0.0012 deg grid spacing, all accomplished within COAMPS-OS (denoted by the green background). The figure also shows the SWAN and COAMPS results used to drive the Delft3D hydrodynamic surf zone model at 40 m grid spacing. The Delft3D products were then used in the NSW Seal Delivery Vehicle (SDV) Certification Exercise (CERTEX).

RELATED PROJECTS

This project is one of a number of coordinated and inter-related projects at NRL for development of a high-resolution forward-deployed navy forecasting and nowcasting capability in the oceanography and meteorology areas. The companion coupled modeling project at NRL-SSC is supported by another ONR Award and the PI is Rick Allard (NRL Code 7322). Other related projects include:

- Battlespace Environmental Assessment for Situational Awareness [PI: Cook – NRL Base] addressing development of a coupled air-ocean data assimilation capability.

- Air-Ocean Coupling in the Coastal Zone [PI: Pullen – NRL Base 6.1] addressing basic research issues related to the identification and understanding the interaction between the ocean and the atmosphere in the littoral region.

- Assessing the Effectiveness of Sub-mesoscale Ocean Parameterizations (AESOP) [PI: Hodur – ONR DRI] studying sub-mesoscale parameterizations for high-resolution (regional scale) models with a strong focus on multi-scale interactions and acquisition of new field data.

- Hybrid Coordinate Ocean Model (HYCOM) [PI: Pullen - NOPP] developing and evaluating a hybrid isopycnal-sigma pressure (generalized) coordinate ocean model, including data assimilation.

- Battlespace Environments Institute (BEI) [PI: Hodur – CHSSI 6.3] migrating existing DoD atmosphere, ocean, and space modeling applications to the Earth System Modeling Framework (ESMF) and assisting in transitioning non-DoD ESMF applications to DoD.

- Littoral Warfare Team Adaptive Sampling Integration [PI: Bishop - RTP] developing and transitioning the capability to the Naval Oceanographic Office (NAVO) to utilize adaptive sampling to improve predictions of sound speed velocity fields for Anti-Submarine Warfare (ASW).

- Coastal Ocean Currents Monitoring Program – Northern and Central California (COCMP-NC) [PI: Doyle – California State through SFSU] monitoring ocean circulation for the region between Pt. Conception and the California/Oregon border using a combination of Surface Current Mapping (SCM) instruments and both 3-D coastal ocean and 2-D San Francisco Bay circulation models.

- NRL is working with several other research groups funded through related programs. The National Center for Atmospheric Research has developed forecasting and nowcasting system technology. WL|Delft Hydraulics has developed Delft3D, an advanced modeling environment for near-shore ocean hydrodynamics, waves, and sediment transport.

- NRL and the NATO Undersea Research Centre (NURC) have a joint research program to evaluate and validate the coupled air-sea modeling system.

PUBLICATIONS

Cook, J., M. Frost, G. Love, L. Phegley, Q. Zhao, D. Geiszler, J. Kent, S. Potts, D. Martinez, T. Neu, D. Dismachek, L. McDermid, 2007: The U.S. Navy's on-demand, coupled, mesoscale data assimilation and prediction system. *22nd Conference on Weather Analysis and Forecasting/18th Conference on Numerical Weather Prediction. 25-29 June 2007, Park City, UT.*

Cook, J., M. Frost, G. Love, J. Pullen, Q. Zhao, R. Allard, T. Campbell, J. Dykes, P. Martin, P. Posey, C. Rowley, D. Geiszler, J. Kent, S. Potts, D. Martinez, P. May, T. Neu, D. Dismachek, and L. McDermid, 2007: A coupled air-sea mesoscale data assimilation and prediction system for U.S. Navy operations. *Presentation at 7th Conference on Coastal Atmospheric and Oceanographic Prediction and Processes, 10-13 September 2007, San Diego, CA.*